DOE/NNSA/NA-22-NEMRE-2002

NATIONAL NUCLEAR SECURITY ADMINSTRATION

Nuclear Explosion Monitoring Research and Engineering Program

STRATEGIC PLAN

s Ratio

Ampere's law

$$\oint \vec{\mathbf{B}} \cdot \mathbf{d}\vec{\mathbf{s}} = \mathbf{\grave{\imath}}\,_0\mathbf{i} + \frac{\mathbf{1}}{\mathbf{c}^2}\frac{\partial}{\partial \mathbf{t}}\oint \mathbf{EdA}$$

$$\nabla \times \mathbf{B} = \frac{4\pi k}{\mathbf{c}^2}\mathbf{J} + \frac{\mathbf{1}}{\mathbf{c}^2}\frac{\partial \mathbf{E}}{\partial \mathbf{t}}\mathbf{B}; \qquad k = \frac{1}{4\pi\varepsilon_0}$$

Coaxial electric field

$$-E(r) = -\frac{\rho}{2\varepsilon}r + \frac{V + (\rho/4\varepsilon)(r_2^2 - r_1^2)}{r\ln(r_2/r_1)}$$

Aerosol deposition in tubes

$$\frac{c_{out}}{c_{in}} = 1 - \frac{4}{\sqrt{\pi}}\sqrt{\frac{DL}{uR^2}}$$

Fermi's Golden Rule

$$\langle\beta|H|\alpha\rangle = -\sum_n \frac{\langle\beta|H|n\rangle\langle n|H|\alpha\rangle}{E_n - E_\alpha}$$

Binomial Distribution

$$p(x) = \frac{n!}{(n-x)!\,x!}p^x(1-p)^{n-x}$$

Klein-Nishina

$$\frac{d\sigma}{d\Omega} = Zr_0^2\left(\frac{1}{1+\alpha(1-\cos\theta)}\right)^2\left(\frac{1+\cos^2\theta}{2}\right)\left(1 + \frac{\alpha^2(1-\cos\theta)^2}{(1+\cos^2\theta)(1+\alpha(1-\cos\theta))}\right)$$

Germanium depletion voltage

$$d = \left(\frac{2\varepsilon V}{eN}\right)^{1/2}$$

Troposphere residence time of 90Sr

$$1 - C = \frac{-S_0 + T\exp(\lambda_{89} - \lambda_{90})t}{T_0 - S_0}$$

Compton scattering

$$h\nu' = \frac{h\nu}{1 + \frac{h\nu}{m_0c^2}(1-\cos\theta)}$$

Charge collection

$$Q(t) = \frac{q_0}{\ln(r_2/r_1)}\left[\ln\left(1 + \frac{v_e t}{r_0}\right) - \ln\left(1 - \frac{v_h t}{r_0}\right)\right]$$

uction

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial \mathbf{t}}$$

Nuclear explosion monitoring and the research and engineering supporting it are, to the surprise of many outside the field, computationally intensive. Equations that form the scientific foundation of our research are displayed on the cover.

National Nuclear Security Administration

Los Alamos NATIONAL LABORATORY

Sandia National Laboratories

Lawrence Livermore National Laboratory

Pacific Northwest National Laboratory
Operated by Battelle for the U.S. Department of Energy

Comments on this document may be directed to Program Manager: Leslie A. Casey, DOE/NNSA/NA-22, 202-586-2151, or via the feedback feature of the Program web site (see inside back cover for url).

The research and engineering on this program involve close collaboration among the laboratories whose logos are displayed here -- Los Alamos National Laboratory, Lawrence Livermore National Laboratory, Pacific Northwest National Laboratory, and Sandia National Laboratories -- and input from users and other contributors (e.g., universities and provate sector researchers). This program is conducted under the guidance of and funded by the Office of Nonproliferation Research and Engineering within the Office of Defense Nuclear Nonproliferation of the National Nuclear Security Administration.

print date: January 2002

NATIONAL NUCLEAR SECURITY ADMINISTRATION

Nuclear Explosion Monitoring Research and Engineering Program Strategic Plan

DOCUMENT ROADMAP

FOREWORD

The threat of a nuclear detonation, whether intentional or accidental, that could kill thousands and inflict widespread catastrophic damage, is still with us, even though the Cold War is over. The 1998 nuclear weapons tests in India and Pakistan, the persistent and well-documented efforts by other states to develop nuclear weapons, and the potential that sub- or trans-national terrorist entities could obtain nuclear weapons all mean that the United States must remain vigilant to deter and prevent nuclear attacks.

It is far better to detect and characterize a nuclear weapon in the testing phase and exert pressure on the proliferator to cease and desist than it is to counter an actual nuclear weapons attack, or, worse yet, deal with its aftermath. The Department of Energy/National Nuclear Security Administration (NNSA) Nuclear Explosion Monitoring Research and Engineering (NEM R&E) Program is a unique national asset dedicated to providing knowledge, technical expertise and products to US agencies responsible for monitoring nuclear explosions in all environments. This program has a long and impressive track record of success in turning scientific breakthroughs into tools for use by operational monitoring agencies in fulfilling validated national requirements. The NEM R&E program has traditionally supported these requirements with a variety of technologies.

The NNSA and its predecessors, in cooperation with the National Laboratories, is home to the US nuclear stockpile stewardship program, which is a cornerstone of US nuclear deterrence policy. The nuclear weapons design and effects expertise and multi-billion-dollar national investment that reside at the National Laboratories provide a unique, full-scope, and multi-disciplinary scientific capability that supports the US in realizing its nuclear explosion monitoring goals.

We reaffirm our commitment to accomplish our mission, and this strategic plan is our blueprint for success.

—Robert E. Waldron
Assistant Deputy Administrator
for Nonproliferation Research and Engineering
National Nuclear Security Administration

PROGRAM MISSION

To develop, demonstrate, and deliver advanced technologies and systems to operational monitoring agencies to fulfill US monitoring requirements and policies for detecting and characterizing nuclear explosions.

KEY PROGRAM ELEMENTS

Integration of New Monitoring Assets

Advanced Event Characterization

Next-Generation Monitoring Systems

The Problem We Face

Forewarned is Forearmed

At present, the established nuclear weapon states — the United States, Russia, the United Kingdom, France, and China — have suspended their nuclear weapons test programs, and we anticipate that they will continue to respect nuclear weapons testing moratoria. India and Pakistan tested in 1998, but each has declared its intention to desist from further testing, if the other does so. Despite strong pressures from the rest of the world, Iraq continues to attempt to pull together a nuclear weapons development program. Other proliferators, from rogue nations to sub- or trans-national terrorist groups, are continuing their quests for nuclear weapons.

A proliferant nation or group may be able to design a crude, heavy (consequently difficult to deliver) nuclear weapon. However, in order to either decrease the size and weight of the weapon, so that it could be delivered on a sophisticated platform such as a missile, or increase the yield, a proliferator would likely need to conduct a test. Detecting a first test of a nascent nuclear weapons program or a test to improve the capability of an established nuclear weapons program allows the US to be forewarned and to preemptively deal with the testing entity before it can contemplate using its weapons.

No single technology has the capability to monitor nuclear explosions in all of the environments in which they might occur. The Air Force Technical Applications Center (AFTAC), the US agency charged with nuclear treaty monitoring, historically has woven together an integrated system of complementary satellite-mounted optical, radiofrequency (RF), and radiation detection technologies and ground-based seismic, hydroacoustic, infrasound, and radionuclide technologies to accomplish its mission. Optical, RF, x-ray, and nuclear radiation sensors mounted on satellite systems detect nuclear explosions in the atmosphere and space. Seismic systems detect subsurface explosions. Hydroacoustic systems detect explosions under and near the surface of the oceans. Infrasound systems detect shallow-buried and atmospheric events. Radionuclide systems detect radioactive gases or particulates that may have resulted from a nuclear explosion. Detections from all these systems are screened by advanced automated data processing technologies, which flag suspect events for further scrutiny by human analysts.

Our delivery of products developed under key program elements (next section) will continue to provide US monitoring agencies with the best tools for carrying out their nuclear explosion monitoring missions. For a description of the previous NNSA accomplishments with space-based and ground-based technologies employed in the monitoring systems, see *The Historical NEM R&E Accomplishments of NNSA — The Right Agency for the Job* at the end of this document.

Program Structure and the Road Ahead

The policy and technology environment in which the NNSA/NEM R&E program operates is dynamic. Monitoring requirements change as new threats are identified and old threats are re-evaluated. At present, the US is deploying new assets as part of ongoing efforts to augment national technical means as others are building the international monitoring system. To address this rapidly evolving state of affairs, the NEM R&E program is structured around three program elements.

Integration of New Monitoring Assets

The purpose of this program element is to provide operationally useful data and software products, for example, through calibration of new monitoring stations and sensors as they are added to existing networks. Calibration in a monitoring context has many meanings. Calibration of the instruments themselves is necessary for quality control and detailed analysis of the data and is well understood and straightforward. For the ground-based seismic waveform technologies, however, calibration also refers to the medium through which the waves pass. The performance of a given station will vary considerably depending on the location where it is deployed, and an extensive, very labor-intensive research effort is required to account for these regional variations. Without such regional corrections, estimates of an event's location can be in error by hundreds of kilometers and other important signal characteristics may be misinterpreted. A major thrust of our efforts is acquiring the necessary characterization information and supplying it in an operationally useful form to the analyst. To address these objectives, the NEM R&E program has developed a sophisticated software and database system, known as the Knowledge Base[1] (KB). Since seismic path calibration requires months to years of data from the station and detailed ground truth,[2] the sooner these calibrations can occur the better prepared the US will be to monitor nuclear explosions.

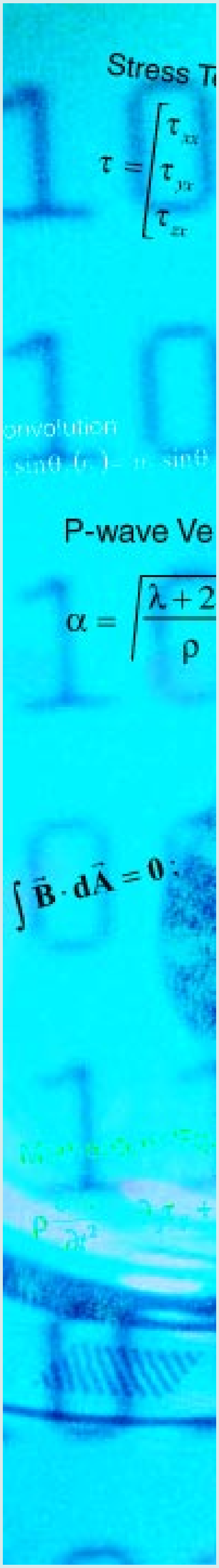
Advanced Event Characterization

Research and engineering to produce technologies for advanced event characterization are crucial for refining detection, location, identification, and characterization for nuclear explosions of very low magnitude anywhere they might occur. There are several signature observables from tests in each environment; the information they contain is complementary and a monitoring system that incorporates sensors for observing each of these phenomena is needed to fully characterize the tests.

The monitoring environments addressed by satellite sensor systems, which are designed for both nuclear test monitoring and support of war fighting, include the earth's atmosphere (0- to 30-km altitude), the transition region (30- to 100- km altitude), and near-space (100- to 100,000-km altitude). Any major change in national requirements, as occurred when attention shifted from cold-war concerns to proliferation concerns, usually calls for substantial changes in the technical approaches used by the satellite sensors. In such cases the research and engineering start with laboratory proofs-of-principal and culminate, whenever possible, with on-orbit demonstration/validation experiments. These proven technologies are then designed into operational systems that are delivered to operational users. Satellite systems are capable of providing an exact location and a thorough characterization of an atmospheric, transition region, or near-space event, if all available techniques are utilized.

Infrasound detection complements our satellite capability in the atmosphere, and this technology is particularly well suited for use in cooperative programs with other nations. Radionuclide monitoring is critical in establishing unequivocal identification of nuclear events and characterizing the sources.

Seismic and hydroacoustic detection systems provide the primary means to effectively monitor subsurface nuclear explosions. Our experience with nuclear tests at the Nevada Test Site has shown that without some prior knowledge of the propagation medium, the uncertainty in a yield estimate using these methods can be as high as a factor of ten. However, with some knowledge, the uncertainty can be cut to a factor of two, and with very detailed knowledge, it can be cut even further. We are currently engaged in an effort to characterize the regional seismic properties of Western China, the Middle East and North Africa, and the Former Soviet Union. Once these studies are complete, we will turn our attention to ways of improving the overall data processing performance of monitoring networks.



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[1] To effectively detect small events and distinguish those that are likely to be nuclear from background events such as earthquakes, mining, military, etc., the US monitoring system must process data from a large network of regional monitoring stations. The system must then sift through this large quantity of detected events and quickly identify those that require further action. Processing these events swiftly and with high confidence requires that detailed knowledge about the earth be available to both automated processing systems and human experts. The Knowledge Base (KB), which can be likened to a warehouse enclosing a large collection of containers each holding a different type of knowledge, is where this detailed information will be stored, maintained, and accessed. Because information in the KB is contributed by a variety of government, university, and private sector researchers, we developed precise guidance for content developers, integrators, and coordination personnel to ensure verification and validation of KB contributions.

[2] Ground truth is the actual *what*, *where* and *when* of an event as confirmed by sources, such as instruments owned by mining companies or university research programs, that are independent of the monitoring system.

Next-Generation Monitoring Systems

The operational US monitoring system (the US Atomic Energy Detection System[3] or USAEDS) will evolve as monitoring networks continue to expand, software and hardware technologies advance, signal processing improves, and the monitoring system requirements become more demanding. We must ensure that next-generation monitoring systems are robust, automated, and user-friendly systems and have backward compatibility with the existing system. We know, based on the constant advancement of science, that our current tools will need to be replaced by revolutionary new technologies emerging from universities, the private sector, and government agencies, particularly DOE/NNSA, which are focused on this arena.

Experience with USAEDS has shown that system configuration changes are very expensive and take many years to fully implement, requiring intervention by knowledgeable experts and considerable investment of time and money. The future monitoring environment will require much more flexible processing that will allow the users themselves to quickly focus on different areas of the world at different levels of detail without time-consuming redesign of the system. The next-generation systems must effectively integrate data from various monitoring technologies, while responding quickly to changes.

Our scientists and engineers are always watching for technologies relevant to the monitoring task and will engineer ways to integrate them into our users' systems. We will lead in the development of concepts for monitoring systems including data processing technologies, as well as in breakthroughs in monitoring technologies.

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[3] USAEDS is operated by the Air Force Technical Applications Center (AFTAC), which is the sole Department of Defense agency operating and maintaining a global network of nuclear event detection sensors. When USAEDS senses an event underground, underwater, in space, or in the atmosphere, AFTAC's experts analyze the event and report findings to the national command authorities.

Challenges and Technology Solutions

Tables 1 and 2 summarize the challenges for the satellite-based and ground-based nuclear explosion monitoring research and engineering programs and the technology solutions we plan to develop to answer those challenges.

Program Management and Coordination

How the DOE/NNSA NEM R&E Program Fits into the National Effort

Figure 1 illustrates the role played by NNSA in the national nuclear explosion-monitoring arena. NNSA enables the realization of US goals and requirements by providing technologies to operational agencies. Data from the events are analyzed, primarily at AFTAC, and then results are provided to policy makers.

Through the technology development expertise at its National Laboratories, NNSA is the enabler. Because the NNSA National Laboratories are the only US entities that have hands-on experience in designing and testing nuclear weapons, they have a unique perspective on technologies required for detecting nuclear explosions, dating back to the beginning of the nuclear age. The NNSA understands both the constraints and the goals of the policy community and the resource needs of the technical community in support of national nuclear-explosion monitoring goals. The DOE/NNSA Laboratories draw on a broad-scope, multidisciplinary cadre of some of the world's foremost technical experts. Over the years, these experts have demonstrated their ability to combine results from their own activities, basic research (by universities and the private sector at home and abroad), and applied research and integrate the technological advances into monitoring systems.

Table 1. Satellite-Based Challenges and Solutions by Program Element

Challenges	Technology Solutions
Program Element: Integration of New Assets	
Incorporate vastly increased data flows from new optical and electromagnetic pulse (EMP) sensors into existing system architecture	Additional downlink capacity through either more ground sites or more storage and bandwidth Sophisticated on-board triggering algorithms Algorithms for ground processing Improved methods of processing/identifying non-nuclear events
Program Element: Advanced Event Characterization	
Increase the absolute sensitivity of sensors for detecting & locating atmospheric nuclear detonations	Focal plane array active pixel technology (thousands of individual optical sensors implemented in a space not appreciably larger than that required for today's single optical sensor) New sensor technologies as integrated circuit technology improves
Provide multi-phenomenology sensing capabilities to increase confidence of identification and improve existing capabilities for characterizing nuclear detonations from space	Autonomous EMP sensors and associated techniques to distinguish RF generated by nuclear explosions from natural phenomena Neutron and gamma-ray sensors on new satellite platforms
Program Element: Next-Generation Monitoring Systems	
Reduce detection thresholds for satellite systems while maintaining low false-event rates	Array-based optical sensors Wide-band RF systems Sophisticated real-time triggering algorithms
Reduce size, weight, and power required for monitoring systems	Advanced electronics, including Z-plane technology and field-programmable gate arrays Multi-function sensors Advanced packaging technologies to allow more electronics integration

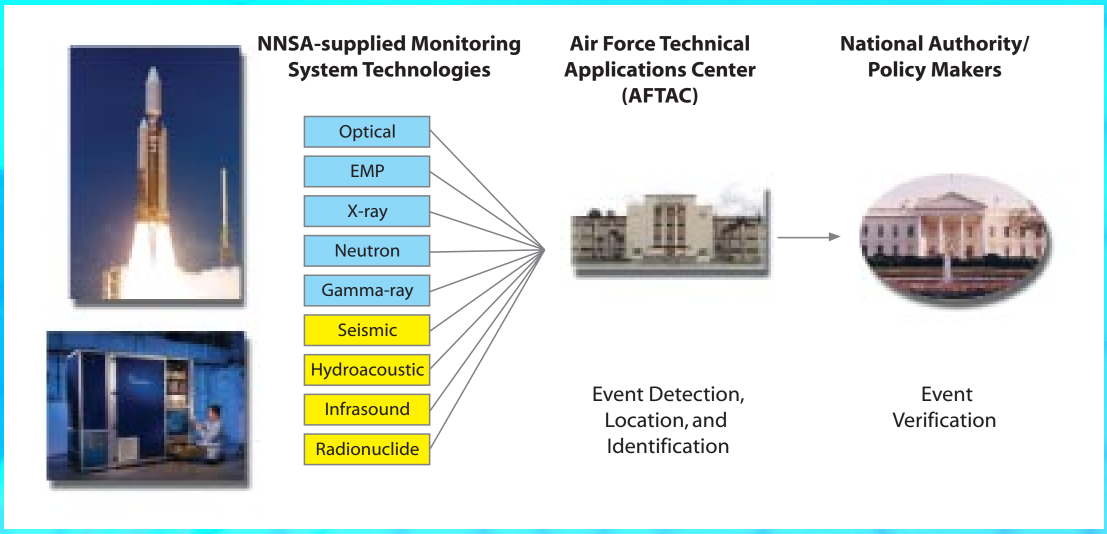

Figure 1. The role of the NNSA-supplied monitoring system technologies

Table 2. Ground-Based Challenges and Solutions by Program Element

Challenges	Technology Solutions
Program Element: Integration of New Assets	
Reduce time and resources required to calibrate new stations	Automated data processing of labor-intensive calibration steps Refined calibration techniques Universal validation techniques
Develop new/improved ground truth collection techniques	Multi-path calibration by reciprocal calibration explosions Overhead imagery as ground truth for reference event locations Partnerships with local scientists
Optimize the Knowledge Base to meet operational requirements	Data acquisition and integration of research products translated into operational form A framework for quantifying and reducing uncertainties and errors in signal and data-processing technologies Exploitation of multi-technology information for event characterizations
Program Element: Advanced Event Characterization	
Data Centers Enhance data acquisition, communication, and interpretation capabilities	Advanced data processing tools to extract the events of interest from the monitoring station data streams and facilitate evaluation by human analysts Extensive Knowledge Base framework Data surety
Seismic Develop a remote characterization capability for regions of interest	Transportable magnitude measurements & procedures Overhead imagery to aid characterization of the geologic environment High-frequency array signal processing
Hydroacoustic Formalize accurate event location and identification methods	Experimentally validated long-range propagation predictions Empirically validated theory for amplitudes of underwater and low-atmospheric nuclear explosions Knowledge Base location grids of bathymetry incorporating signal reflection and blockages
Infrasound Establish accurate event location and identification analysis tools	Efficient automated signal- and event-processing drawing upon a reference event library Advanced analysis and location tools incorporating signal reflection and blockages Source characterization for discriminant development to reduce false alarms, particularly from mining events and bolides
Radionuclide Tailor sensitivity and discrimination methods while reducing maintenance and analysis costs	Analyses that identify new signatures for small nuclear detonations New radiation detection technologies such as pulse shape analysis New materials for more selective, rapid sample preparation and higher resolution detection of characteristic radioactive emissions Station-centric analysis tools to establish the monitoring background levels and to facilitate operations, including state of health
Program Element: Next-Generation Monitoring Systems	
Lead in the development of concepts for monitoring systems including data processing technologies, as well as in breakthroughs in monitoring technologies	Tools and techniques to automatically acquire, store, analyze, display and disseminate/report data and information from a variety of sources and systems using cognitive task analysis and decision-centric design approaches and the latest in distributed, object-oriented design methodologies Guarantee data surety, including techniques for system security, reliability, and data integrity Backward compatibility of systems

How We Are Structured For Management Success

In carrying out our research and engineering program, our management philosophy is to be ever mindful of the needs of our various stakeholders, from the US private sector to the international community to government users and ultimately to US taxpayers.

Partnering

We partner with our users to leverage assets, including the budget and technology assets, of several agencies working together on nuclear explosion monitoring issues. We use Memoranda of Understanding (MOUs) as formal and informal management partnering tools for coordination with the users. MOUs are critical for delineating roles, responsibilities, and areas of cooperation.

As we approach the hand-over point, where our technologies become operational systems serving our country, the users themselves help fund that final step to ensure the success of the transfer process. In several cases, multimillion dollar Department of Defense (DoD) acquisitions have followed this process, with full NNSA consultation and support.

We work closely with the Air Force to coordinate specifications and delivery schedules for satellite instruments, so they can be integrated smoothly onto their host satellites. We also provide expert assistance for pre-launch and on-orbit testing. The DOE/NNSA Knowledge Base is an essential component of the operational AFTAC data processing pipeline and must integrate seamlessly into it, a systems design challenge that is no trivial task. We have worked with national and international partners who have funded the labs to conduct site surveys for new infrasound stations. We have also worked with private companies to transition our prototype radionuclide sampler-analyzers to commercially produced versions.

Collaboration with Other Organizations in the US

A key to optimal external collaboration is enabling each entity to do what it does best. The NEM R&E program and other government agencies sponsor universities and private sector researchers who excel at specific research projects that do not require the multi-billion dollar infrastructure and broad multi-disciplinary staff of a National Laboratory. The National Laboratories then fill in the gaps between these targeted research endeavors, optimize their results, and provide overall integration. To this end, we are publishing and maintaining contributor guides that define the process of “vetting” and integrating new data sets into information products for the KB.[4]

Many of our partnering activities do not involve transfer of funds. For example, we coordinate each year with the Defense Threat Reduction Agency (DTRA) to produce a joint research plan, so there is mutual cooperation and no duplication of effort between the two agencies. DTRA and DOE/NNSA also cooperate in peer reviews and program reviews of ongoing research in both agencies. We participate in mutual data sharing with the United States Geological Survey,[5] and we assist in product integration to fold the contributions of private sector researchers into the overall monitoring system.

[4] D. Carr, S. Moore, H. Armstrong, L. Wilkening, M. Chown, E. Shepherd, T. Edwards, R. Keyser, C. Young, A. Cogbill, J. Aguilar-Chang, A. Velasco, S. Ruppert, (2/00), *Knowledge Base Contributor's Guide*, Sandia National Laboratories Report SAND2000-0442 and D. Gallegos, D. Carr, P. Herrington, J. Harris, C. Edwards, S. Taylor, J. Zucca, D. Harris, N. Wogman, D. Anderson, L. Casey, (11/01) *The Integration Process Design for Incorporating Information Products into the National Nuclear Security Administration Knowledge Base*, Sandia National Laboratories Report SAND2001-2960.

[5] In addition to AFTAC and others, we partner with the United States Geological Survey (USGS), which is responsible for monitoring national and worldwide seismicity and reporting to national and international emergency response agencies, and to other interests including the media and the general public. USGS contributes geological expertise to the national effort and appropriate products to the NNSA Knowledge Base.

KEY MEMORANDA OF UNDERSTANDING BETWEEN NNSA AND OTHER AGENCIES

Tri-party MOU amongst Air Force Technical Applications Center (AFTAC) and United States Geological Survey (USGS) and National Nuclear Security Administration (NNSA), dated May 9, 2001.

Integration, Launch, and Spaceflight of the Space and Atmospheric Burst Reporting System Validation Experiment — tri-party Memorandum of Agreement amongst DoD Space Test Program (STP) and US Air Force (USAF) Defense Support Program (DSP) and Department of Energy (DOE), dated September 22, 1999.

US Nuclear Detonation Detection System (USNDS) – four-party MOU amongst USAF Space Command and USAF Space and Missile Systems Center (SMC) and AFTAC and DOE, dated January 8, 1997.

To foster and strengthen the vital links between NNSA laboratory scientists and the wider community, NNSA partners with DTRA in support of an annual research symposium on monitoring topics, attended by university, private sector, and NNSA laboratory scientists. The result is a very positive and broad contact and collaboration between scientists and engineers in support of our combined objective. This forum has produced numerous cases of cooperation, sharing of assets, and coordination of results.

International Cooperation

National and international organizations are in the middle of an ongoing process to increase coverage of the globe by installing or upgrading networks of ground-based monitoring stations for a variety of reasons (e.g., earthquake monitoring, monitoring by the Provisional Technical Secretariat for the Comprehensive Nuclear-Test-Ban Treaty, Global Seismic Network operation, hazard mitigation, regional stability). The more stations around the globe producing and sharing high-quality data, the better the identification and location capability; the more international cooperation, the more data for the US to utilize and the less cost to US taxpayers. Like the US, other countries are in the process of installing and upgrading monitoring stations, and we are cooperating with and assisting them, when it complements or supports US interests.

Budget

The NEM R&E target budget, which is approximately $100M per year, is designed to provide valuable products to the user community and to be a natural progression from our previous successful activities. This budget is designed to deliver integrated systems that dovetail into user satellite- and ground-based systems deployment schedules.

Actual appropriations are made annually and vary in complex ways. A variety of factors impacts the budget, such as administration budget guidance, actual Congressional appropriations, user modifications to deployment schedules, research results that complete some tasks and begin new areas of promising research, and interagency programmatic transfers.

Scheduling Considerations

Our programmatic schedules are closely coordinated with our customers. The following planning assumptions come into play in our scheduling.

Satellite–based systems

- **Approximately three operational payloads per year delivered to Air Force hardware integrating contractors**
- **Launch schedules and satellite technology changes driven by Air Force requirements**
- **Demonstration/validation experiments for future generation technologies**

Ground–based systems

- **Biennial federal and non-federal solicitation using monies from two years per solicitation**
- **Core integration function including regular delivery of Knowledge Base releases**
- **New seismic station installation, roughly 3-4 per year for the next ten years, guiding reprioritization of calibration resources with the user**

The Historical NEM R&E Accomplishments of NNSA — The Right Agency for the Job

Expertise plus Experience

A truly impressive array of technologies has been developed and transferred to monitoring agencies by DOE/NNSA (and its predecessors) over the last 55 years to enable monitoring of nuclear explosions and verification of the many treaties that have played a role in preventing nuclear war. We have contributed substantially to the monitoring technologies used by the USAEDS. Today our technologies are monitoring the Earth from below the oceans, under and on the continents, high in the atmosphere, and far overhead in space. Over many years, we have provided expert support for policy formulations and creative solutions for technological requirements related to nuclear explosion monitoring.

Since the initial nuclear-weapon test at Trinity Site near Alamogordo, New Mexico, in 1945, US policy has sought to limit the spread (proliferation) of this awesome destructive power, but at the same time to monitor worldwide in order to detect the activities of proliferators. Over time, the US has employed various strategies to prevent the proliferation of nuclear weapons, including becoming party to several treaties such as the Limited Test Ban Treaty (LTBT), the Nuclear Non-Proliferation Treaty (NPT), and the Threshold Test-Ban Treaty (TTBT).[6]

Over the years, NEM R&E staff have been instrumental in developing the actual sensors and, equally important to the capability, developing methods for interpreting the data they produce. Incorporating these diverse technologies into an integrated system takes advantage of the synergy provided by complementary measurement techniques, and often provides the important advantage of multi-phenomenology detection. Furthermore, it allows us to capitalize on similarities in the research, development, and engineering tasks associated with the different technologies. The reward for success is a cost-effective, extremely powerful monitoring system capable of global, full-time detection and characterization of nuclear explosions which supports national decision-making processes.

An important characteristic of our applied research program is our emphasis on developing products that can be transitioned directly into operational monitoring systems. This emphasis on real-world applications is facilitated by close coordination of product deliveries with key operational schedules (e.g., schedules for satellite launches, data processing upgrades, equipment deployment).

Table 3 gives specific examples of science-based methods and technologies for enhanced detection, location, and identification of low-yield nuclear explosions under development or already developed by the NEM R&E program.

[6] For more information about the LTBT, the NPT, the TTBT, and other treaties relevant to nuclear explosion monitoring, go to http://dosfan.lib.uic.edu/acda/treaties.htm

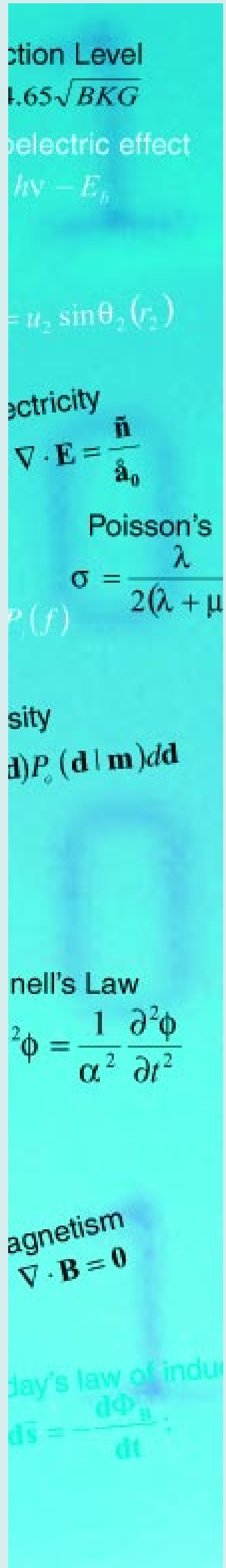

Table 3. NNSA-Developed Nuclear Explosion Monitoring Technologies	
Satellite Based	**Ground Based**
Array-based optical detectors (under development)	Technology for data authentication (1998-2001)
Combined nuclear radiation/particle sensors (under development)	A non-explosive source for ocean-basin scale hydroacoustic system calibration (2000-present)
LAZAP and RZAP for periodic calibrations (ongoing) [7]	The theoretical foundation and numerical modeling techniques for shelter structures for noise reduction at infrasound monitoring stations (1999-present)
Combined dosimeter/x-ray detectors (first launched 2001)	Technology for detecting in real time short-lived radioactive noble gases released during nuclear explosions -- the Automated Radioxenon Sampler Analyzer or ARSA[8] (1999)
Autonomous electromagnetic pulse (EMP) sensors validated on the FORTE satellite (launched 1997)	A suite of analytical tools for automating signal characterization and maximizing the skills of analysts (1998-present)
Imaging x-ray detectors validated on the ALEXIS satellite (launched 1993)	Technology for detecting in real time short-lived particulates released during nuclear explosions -- Radioactive Aerosol Sampler Analyzer or RASA (1998)
Optical and EMP sensors (first launched 1965 for the LTBT)	Significant advances in reliability of measurement corrections for location and discrimination through a new application of a proven *kriging*[9] paradigm (1997-99)
Detectors sensitive to x-ray, gamma-ray, and neutron emissions (first launched 1963 for the LTBT)	A vast Knowledge Base that combines data and information in different formats from multiple sources into a unified framework. This quality-controlled and highly organized framework encapsulates the foundation for the NEM R&E ground-based program elements (1997-present)
	A prototype low-frequency sound (infrasound) detection system ready for transfer to users (1997)
	The Magnitude and Distance Correction (MDAC) technique allowing for operational regional seismic event identification (1996-present)
	Participation in the design and execution of the Non-Proliferation Experiment[10] (1993)
	Stable and transportable event magnitude yield estimates using regional seismic coda,[11] accurate even with very limited data as, for example, in areas where there's only a single station to collect data (1990s)
	Steady improvements to regional discrimination techniques. Regional monitoring was not considered viable until DOE/NNSA researchers demonstrated its capability (1980s and 1990s)
	US on-site yield estimation technology (CORRTEX) that was subsequently negotiated for verification of the TTBT (1985)
	In collaboration with others, the concept of combining multiple seismic sensors into an arry for regional monitoring, for example the NORESS seismic array, developed in partnership with Norway in 1983, and employing a concept since applied to infrasound sensors as well (1980s)
	A Regional Seismic Test Network[12] (RSTN) to demonstrate the feasibility of National Seismic Stations (NSSs) -- stand-alone autonomous regional seismic monitoring sites transmitting to satellites (1978-1987)

[7] Newly launched satellite-borne optical sensors are pulsed with a laser beam (LAZAPed) to ensure their proper operational capability. Likewise, RF sensors are calibrated with an RF pulser (RZAPed).

[8] Field experiments in both the US and Germany proved that this technology could discriminate radiation releases from a nuclear detonation from those of a nuclear power reactor. The experiments further proved that the sampling time was short enough to take measurements of the rapidly moving plume, which passed by the samplers in less than 10 hours.

[9] *Kriging* is a "smart" spatial interpolation technique with a built-in error estimation.

[10] The Non-Proliferation Experiment was a comprehensive experiment to determine differences between the signatures of checmical and nuclear explosions. A broad range of transient phenomena was recorded both on site and off, including seismic, EMP, hydroacoustic, and infrasound signals, as well as migration of tracer gases released from a canister placed in the explosive chamber prior to the test. To try to detect the cavity, pre- and post-shot aerial surveys were made with multi-spectral imagery, and post-shot electrical and magnetic measurements were taken.

[11] A coda is the scattered energy observed at the tail end of a seismogram.

[12] The RSTN was a cornerstone of Tri-Lateral (US, UK, and Soviet Union) attempts at a comprehensive test ban treaty negotiated during the 1980s but never finalized.

For more information:

The NNSA/NEM R&E Program World Wide Web Site facilitates coordination among fellow researchers and users on the best use of research products, data, and results. Please visit us at

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Stress Tensor

$$\tau = \begin{bmatrix} \tau_{xx} & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \tau_{yy} & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \tau_{zz} \end{bmatrix}$$

Wave Equation

$$\nabla^2\phi = \frac{1}{\alpha^2}\frac{\partial^2\phi}{\partial t^2}$$

Currie's Detection Level

$$L_d = 2.33 + 4.65\sqrt{BKG}$$

Photoelectric effect

$$E_{e-} = h\nu - E_b$$

Strain Tensor

$$e = \begin{bmatrix} \frac{\partial u_x}{\partial x} & \frac{1}{2}\left(\frac{\partial u_x}{\partial z} + \frac{\partial u_z}{\partial x}\right) & \frac{1}{2}\left(\frac{\partial u_x}{\partial z} + \frac{\partial u_z}{\partial x}\right) \\ \frac{1}{2}\left(\frac{\partial u_y}{\partial x} + \frac{\partial u_x}{\partial y}\right) & \frac{\partial u_y}{\partial y} & \frac{1}{2}\left(\frac{\partial u_y}{\partial z} + \frac{\partial u_z}{\partial y}\right) \\ \frac{1}{2}\left(\frac{\partial u_z}{\partial x} + \frac{\partial u_x}{\partial z}\right) & \frac{1}{2}\left(\frac{\partial u_z}{\partial y} + \frac{\partial u_y}{\partial z}\right) & \frac{\partial u_z}{\partial z} \end{bmatrix}$$

Convolution

$$u_1 \sin\theta_1(r_1) = u_2 \sin\theta_2(r_2)$$

Gauss' law for electricity

$$\oint \vec{\mathbf{E}} \cdot d\vec{\mathbf{A}} = \frac{\mathbf{q}}{\text{å}_0}; \qquad \nabla \cdot \mathbf{E} = \frac{\text{ñ}}{\text{å}_0}$$

Poisson's

$$\sigma = \frac{\lambda}{2(\lambda +}$$

Young's Modulus

$$E = \frac{(3\lambda + 2\mu)}{(\lambda + \mu)}$$

MDAC

$$\log A_{ij}(f) = \log G(r_{ij}, r_0) + \log S_i(f) - \frac{\pi f \log e}{Q(f)v} r_{ij} + \log P_j(f)$$

Gamma Peak Shape

$$F(e) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(e-e')^2}{2\sigma^2}}$$

Marginal posterior probability density

$$P_L(\mathbf{m}) = \oint_D P_L(\mathbf{d},\mathbf{m})dd = P_p(\mathbf{m})\oint_D P_p(\mathbf{d})P_G(\mathbf{d}\,|\,\mathbf{m})dd$$

Expected values

$$\langle\mathbf{m}\rangle = \mathbf{m}_p + \left[\mathbf{G}^T\mathbf{C}_d^{-1}\mathbf{G} + \mathbf{C}_m^{-1}\right]^{-1}\mathbf{G}^T\mathbf{C}_d^{-1}(\mathbf{d} - \mathbf{G}\mathbf{m}_p)$$

P-wave Velocity

$$\alpha = \sqrt{\frac{\lambda + 2\mu}{\rho}}$$

Snell's Law

$$\nabla^2\phi = \frac{1}{\alpha^2}\frac{\partial^2\phi}{\partial t^2}$$

Beta decay density of states

$$\rho(E) = \frac{V^2}{(2\pi h)^6}\frac{d}{dE_{max}}\oint p_e^2 dp_e d\Omega_e p_{\bar{\nu}}^2 dp_{\bar{\nu}} d\Omega_{\bar{\nu}}$$

S-wave Velocity

$$\beta = \sqrt{\frac{\mu}{\rho}}$$

Momentum Equation

$$\rho\frac{\partial^2 u_i}{\partial t^2} = \partial_j \tau_{ij} + f_i$$

Bulk Modulus

$$\kappa = \lambda + \frac{2}{3}\mu$$

Gauss' law for magnetism

$$\oint \vec{\mathbf{B}} \cdot d\vec{\mathbf{A}} = \mathbf{0}; \qquad \nabla \cdot \mathbf{B} = \mathbf{0}$$

Minimum Detectable Concentration

$$MDC = \frac{L_d}{\varepsilon(E)F_\gamma V}$$

Faraday's law of indu

$$\oint \vec{\mathbf{E}} \cdot d\vec{\mathbf{s}} = -\frac{\mathbf{d}\Phi_{\mathbf{B}}}{\mathbf{dt}};$$